

ASTROMETRY OF THE DYNAMICAL EJECTION OF THE BECKLIN-NEUGEBAUER OBJECT FROM θ^1 ORI C

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ABSTRACT

We show that the proper motion of the Becklin-Neugebauer (BN) object is consistent with its dynamical ejection from the θ^1 Ori C binary, contrary to recent claims by Gómez et al. Continued radio observations of BN and future precise astrometric observations of θ^1 Ori C with SIM and the Orion Nebula Cluster with GAIA can constrain the properties of this ejection event, with implications for theories of how the nearest example of massive star formation is proceeding.

Subject headings: stars: formation — stars: kinematics

1. INTRODUCTION

Understanding massive star formation remains one of the most challenging and important problems of contemporary astrophysics (Beuther et al. 2007; Zinnecker & Yorke 2007). The complexity of the process means that massive star formation theories, such as the turbulent core model (McKee & Tan 2003), the competitive accretion model (Bonnell & Bate 2006) and stellar coalescence model (Bonnell et al. 1998; Clarke & Bonnell 2008) require close testing against observed systems. The closest forming (i.e. accreting) massive star is thought to be radio source I (Menten & Reid 1995) within the Orion Nebula Cluster (ONC), at a distance of 414 ± 7 pc (Menten et al. 2007, adopted throughout), in the Kleinmann-Low (KL) region. As reviewed by Tan (2008), this source has been used as observational evidence in support of all three of the above theories. Part of this confusion is due to the Becklin-Neugebauer (BN) object, 9.9'' to the NW (Fig. 1), which is a fast moving (radio-ONC-frame proper motion of $\mu_{\text{BN}} = 13.2 \pm 1.1$ mas yr⁻¹, i.e. $v_{2\text{D},\text{BN}} = 25.9 \pm 2.2$ km s⁻¹ towards P.A._{BN} = $-27^\circ.5 \pm 4^\circ$, Plambeck et al. 1995; Gómez et al. 2008) embedded B star ($L_{\text{BN}} = (2.1 - 8.5) \times 10^3 L_\odot$, Gezari, Backman & Werner 1998, equivalent to a zero age main sequence mass $m_{\text{BN,zams}} = 9.3 \pm 2.0 M_\odot$). This proper motion implies that BN has been moving through the KL region and made a close, possibly coincident, passage with source I about 500 years ago. Thus to understand the nearest example of massive star formation, we need to understand the origin of BN's motion.

Including the $(+21) - (+8) = +13$ km s⁻¹ radial velocity of BN with respect to the ONC mean (Scoville et al. 1983; Walker 1983), the 3D ONC-frame velocity of BN is $v_{3\text{D},\text{BN}} = 29 \pm 3$ km s⁻¹, and its kinetic energy is $E_{\text{BN}} = (8.3 \pm 2.3) \times 10^{46} (m_{\text{BN}}/10 M_\odot)$ ergs. BN is very likely to have formed somewhere in the ONC and then attained its high speed by a close interaction with a massive multiple stellar system followed by dynamical ejection (Poveda, Ruiz & Allen 1967).

Tan (2004) proposed BN was launched from the θ^1 Ori C binary (also shown in Fig. 1), since this is the only stellar system in the ONC known to have all the physical properties required by this scenario: (1) a location along BN's past trajectory (§2); (2) an (optical)-ONC-frame proper motion ($\mu_{\theta^1\text{C}} = 2.3 \pm 0.2$ mas yr⁻¹, van Altena et al. 1988, i.e. $v_{2\text{D},\theta^1\text{C}} = 4.5 \pm 0.4$ km s⁻¹, towards P.A. _{$\theta^1\text{C}$} = $142^\circ.4 \pm 4^\circ$) that is in the opposite direction to BN (the direction to BN from θ^1 Ori C is a P.A. = $-30^\circ.949$) and is of the appropriate magnitude (the dynamical mass of BN implied by this motion agrees with the estimate of $m_{\text{BN,zams}}$ and is $m_{\text{BN,dyn}} = 8.6 \pm 1.0 M_\odot$ assuming negligible error in $m_{\theta^1\text{C}} = 49.5 M_\odot$ and negligible motion of the pre-ejection triple system in this direction; a pre-ejection motion of 0.35 mas/yr along this axis (§3) would contribute an additional $1.5 M_\odot$ uncertainty); (3) primary ($m_{\theta^1\text{C}-1} = 34 M_\odot$) and secondary ($m_{\theta^1\text{C}-2} = 15.5 M_\odot$) masses greater than m_{BN} (Kraus et al. 2007); (4) a semi-major axis of $a = 17.0 \pm 5.8$ AU (Patience et al. 2008) and thus a total orbital energy ($E_{\text{tot}} = Gm_{\theta^1\text{C}-1}m_{\theta^1\text{C}-2}/(2a) = (2.7 \pm 0.9) \times 10^{47}$ ergs) greater than the sum of BN's kinetic energy and θ^1 Ori C's kinetic energy (1.00×10^{46} ergs) (see Tan 2008 for a review). Note, θ^1 Ori C's recoil in this scenario is large enough to remove it from the Trapezium region (see Pflamm-Altenburg & Kroupa 2006 for theoretical studies of the dynamical decay of Trapezium-like systems) and may be enough to eject it from the ONC completely, with implications for the effectiveness of its ionizing feedback on disrupting the star cluster formation process.

Rodríguez et al. (2005) and Bally & Zinnecker (2005) proposed BN was launched from an interaction with radio source I, which would require this system to be a massive binary, recoiling away from any large scale ($\gtrsim 100$ AU) gas that it was originally accreting. Gómez et al. (2008) used the relative motion to BN with respect to source I to claim that BN could not have made a close passage with θ^1 Ori C, excluding this possibility at the 5-10 σ level.

We show in §2 that if BN's motion is considered in the reference frame of the ONC, then a close (coincident) passage with θ^1 Ori C is allowed by the data, which permits the scenario of dynamical ejection of BN from θ^1 Ori C. In §3 we discuss the potential of future high precision astrometric measurements to constrain the properties of BN's dynamical ejection, which then constrain BN's interaction distance with source I, the mass of source I, and thus the strength of tidal perturbations on the massive protostar during this encounter.

2. ASTROMETRY OF BN IN THE ORION NEBULA CLUSTER

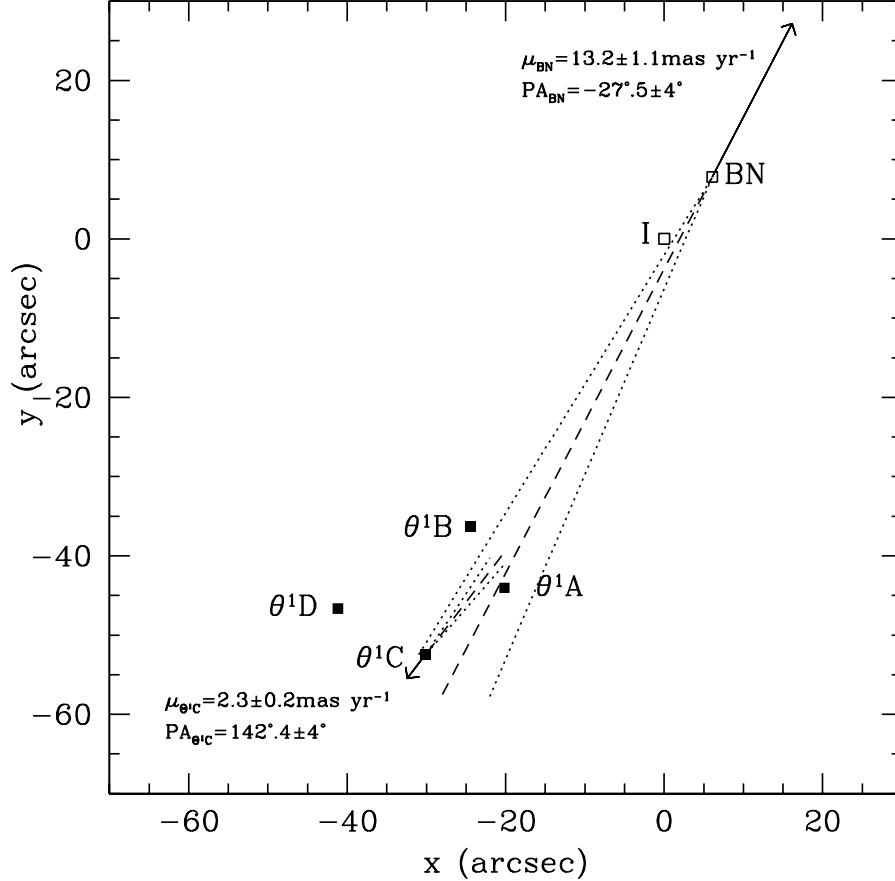


FIG. 1.— This diagram shows the positions of the Trapezium stars θ^1 Ori A, θ^1 Ori B, θ^1 Ori C and θ^1 Ori D that make up the core of the ONC. The positions of radio sources I and BN are also shown. The coordinates are relative to the present position of source I ($\alpha(\text{J2000})=05\ 35\ 14.5141$, $\delta(\text{J2000})=-05\ 22\ 30.556$) (Gomez et al. 2008). The proper motions relative to the cluster of BN (Gomez et al. 2008) and θ^1 Ori C (van Altena et al. 1988) are indicated with the arrows. Past trajectories (dashed line) and 1σ uncertainties (dotted lines) are drawn.

To determine BN's past trajectory through the ONC we use the absolute proper motion of BN ($\mu_\alpha \cos \delta = -5.3 \pm 0.9 \text{ mas yr}^{-1}$, $\mu_\delta = 9.4 \pm 1.1 \text{ mas yr}^{-1}$ (1σ errors); Gómez et al. 2008) and then correct for the motion of the ONC (mean of 35 radio sources within central 0.1 pc of ONC: $\mu_\alpha \cos \delta = +0.8 \pm 0.2 \text{ mas yr}^{-1}$, $\mu_\delta = -2.3 \pm 0.2 \text{ mas yr}^{-1}$; Gómez et al. 2005). The ONC-frame proper motions are shown in Fig. 1. One sees that the past trajectory of BN through the ONC overlaps within the 1σ errors with the present position of θ^1 Ori C. Given the motions of BN and θ^1 Ori C, the time of coincidence (i.e. when the dynamical ejection took place) was 4530 years ago, i.e. about 174 orbital periods of θ^1 Ori C (although the orbital period is only poorly constrained at present to 26 ± 13 years, Patience et al. 2008).

Gómez et al. (2008) excluded a coincidence between BN and θ^1 Ori C because they used the motion of BN with respect to source I (which is measured using relative astrometry to greater accuracy so has smaller error bars), but did not allow for the fact that their data indicate that source I is moving. In the ONC frame this motion is claimed to be $\mu_\alpha \cos \delta = -3.7 \pm 1.2 \text{ mas yr}^{-1}$, $\mu_\delta = -3.4 \pm 1.3 \text{ mas yr}^{-1}$, corresponding to $\mu_I = 5.0 \pm 1.3 \text{ mas yr}^{-1}$ (i.e. $9.9 \pm 2.6 \text{ km s}^{-1}$) towards a P.A. = $+133^\circ \pm 16^\circ$.

We note, as a separate point, that source I is elongated along the NW-SE axis, i.e. towards P.A. $\simeq +135^\circ$ (Reid et al. 2007). If the source exhibits variability affecting the location of the centroid of its emission, then this could lead to an apparent, but false, proper motion. This effect is a potential source of additional uncertainty in the motion reported for source I (and for source n) by Gómez et al. (2008).

Source I is thought to be a massive protostar and a large proper motion would be interesting for theories of massive star formation. Fűrész et al. (2008) measured the distribution of radial velocities in the ONC, finding it could be well fit by a Gaussian with $\sigma_{1D} = 3.1 \text{ km s}^{-1}$, for both the entire cluster and for stars within a $15'$ radius of the Trapezium. Assuming an isotropic velocity distribution, the proper motions should exhibit a Gaussian distribution of motions with $\sigma_{2D} = 4.4 \text{ km s}^{-1}$. In comparison, Source I's claimed motion of $9.9 \pm 2.6 \text{ km s}^{-1}$ is $(2.3 \pm 0.6)\sigma_{2D}$, i.e. not significantly larger than expected of a typical cluster member. Note, Jones & Walker (1988) found $\sigma_{2D} = 2.9 \text{ km s}^{-1}$ from direct

observation of proper motions (adjusted to $d_{\text{ONC}} = 414$ pc), for which source I 's motion would then be $(3.4 \pm 0.9)\sigma_{2D}$. Gómez et al. (2005) found $\sigma_{2D} = 7.6 \text{ km s}^{-1}$ based on proper motions of 35 radio sources, for which source I 's motion would then be $(1.3 \pm 0.3)\sigma_{2D}$. We conclude, in contrast to Gómez et al. (2008), that it is premature to claim that source I has an anomalously large motion compared to other ONC stars.

3. POTENTIAL OF HIGH PRECISION ASTROMETRY WITH SIM

For wide angle absolute astrometry, SIM should be able to achieve a parallax accuracy of about $5 \mu\text{as}$. Assuming a distance of about 400 pc, this will allow a parallax distance measurement accurate to 0.2%, i.e. 0.9 pc.

Once the motions of the primary and secondary components of θ^1 Ori C due to their binary orbit are accounted for, then the absolute proper motion of the system should be known to an accuracy of a few $\mu\text{as/yr}$. By averaging over many stars, an even greater accuracy should be achievable for the absolute proper motion of the ONC with GAIA. Since θ^1 Ori C is moving at a few mas/yr in the ONC frame (van Altena et al. 1988), then the accuracy of the position angle of the direction of motion would be $\sim 0.06^\circ$. Presently it is only known to about 4° .

If, as seems very likely, BN was ejected from θ^1 Ori C, it should have been ejected in exactly the opposite direction to θ^1 Ori C's motion as measured in the center of mass frame of the pre-ejection triple system. Comparison of the ONC-frame motion of θ^1 Ori C with the present position and ONC-frame motion of BN, will yield information on motion of the pre-ejection triple system and any accelerations experienced by the stars since ejection.

The expected size of pre-ejection triple system proper motion is uncertain. If the system (with total mass $\simeq 60M_\odot$) was in kinetic energy equilibrium with the other ONC stars (with, say, typical mass $1.0M_\odot$ and $\sigma_{2D} = 4.0 \text{ km s}^{-1}$), then we would expect it to have a plane of sky motion $\sim 0.52 \text{ km s}^{-1}$ equivalent to a proper motion of 0.26 mas/yr . The observed proper motion dispersion of bright ($V \lesssim 12.5$), i.e. massive, stars is $0.70 \pm 0.06 \text{ mas/yr}$ (van Altena et al. 1988). Assuming a 0.5 mas/yr proper motion for the pre-ejection triple system, of which 0.35 mas/yr would be expected to be tangential to the ejection axis, implies that the ONC-frame proper motion vectors of θ^1 Ori C and BN would be misaligned by 10° from direct opposition. The current observed misalignment is $10^\circ \pm 6^\circ$. Thus, in the limit that subsequent accelerations are negligible, high precision ONC-frame proper motions of θ^1 Ori C and BN (the latter expected from continued radio observations) can constrain the motion of the pre-ejection triple system.

The expected gravitational accelerations of θ^1 Ori C and BN depend on the distribution of mass in their surroundings. Their trajectories are taking them away from the ONC center, so they will be experiencing a deceleration associated with climbing out of the cluster potential. This effect is largest for BN, but it is still small. BN has moved 0.12 pc (projected) from the ejection site, and if the enclosed mass is $500 M_\odot$ (likely to be a conservative upper limit, e.g. Hillenbrand & Hartmann 1998), then for a starting velocity of 30 km s^{-1} , it would have decelerated by only 0.6 km s^{-1} .

Close passage with individual stars can also cause more significant accelerations. θ^1 Ori C's trajectory may have brought it into relatively close proximity with θ^1 Ori A (a B0 star, i.e. $16M_\odot$, $13''$ to the NW, with a visual companion at 100 AU of $4M_\odot$ and a spectroscopic companion at $\sim 1 \text{ AU}$ of $\sim 3M_\odot$, Schertl et al. 2003). However, the relative motion of these stars is only about 1.2 mas yr^{-1} (van Altena et al. 1988) so that the time of closest approach would have been about 10^4 yr ago, long before the proposed interaction of θ^1 Ori C with BN.

More importantly, BN made a close passage to source I about 500 years ago. From the bolometric luminosity of the KL region, source I is estimated to have a protostellar mass of about $20 M_\odot$. As an example of the magnitude of the deflections that can be expected, treating BN as a massless test particle, its deflection angle due to source I is $2.25^\circ (m_{I,*}/20M_\odot)(b/1000\text{AU})^{-1}(v_{\text{BN}}/30\text{km s}^{-1})^{-2}$, where b is the initial impact parameter and v_{BN} is the velocity of BN relative to source I . A direct trajectory from θ^1 Ori C's present position (ideally this would be measured from θ^1 Ori C's position at the time of ejection) to BN's position has a closest projected separation from source I 's present position of $1.5''$ (about 600 AU). Thus an accurate astrometric solution of this system presents us with the unique opportunity of constraining the dynamical mass of source I , the nearest massive protostar, in combination with the true (unprojected) distance of closest approach. The true distance of closest approach is important for evaluating the tidal effects of BN on source I 's accretion disk, which are likely to have enhanced accretion to the star (Ostriker 1995; Moeckel & Bally 2006). Such enhanced accretion is likely to have led to enhanced protostellar outflow activity, thus explaining the $\sim 1000 \text{ yr}$ timescale of the “explosive” outflow from this region (Allen & Burton 1993; Tan 2004).

4. CONCLUSIONS

We have reviewed the latest evidence that BN was dynamically ejected from the θ^1 Ori C binary, finding that θ^1 Ori C has all the physical properties expected in this scenario. We showed that the trajectory of BN is also consistent with this scenario, in contrast to recent claims by Gómez et al. (2008). We discussed how high precision astrometry of θ^1 Ori C with SIM can yield information on the pre-ejection velocity of the system and the size of any subsequent deflections, in particular that of BN caused by close passage with source I , the nearest massive protostar.

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